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ABSTRACT

We are working on developing an alternative technology for storage of hydrogen or natural gas on light-duty vehicles. This technology has been titled insulated pressure vessels. Insulated pressure vessels are cryogenic-capable pressure vessels that can accept either liquid fuel or ambient-temperature compressed fuel. Insulated pressure vessels offer the advantages of cryogenic liquid fuel tanks (low weight and volume), with reduced disadvantages (fuel flexibility, lower energy requirement for fuel liquefaction and reduced evaporative losses). The work described in this paper is directed at verifying that commercially available pressure vessels can be safely used to store liquid hydrogen or LNG. The use of commercially available pressure vessels significantly reduces the cost and complexity of the insulated pressure vessel development effort. This paper describes a series of tests that have been done with aluminum-lined, fiber-wrapped vessels to evaluate the damage caused by low temperature operation. All analysis and experiments to date indicate that no significant damage has resulted. Future activities include a demonstration project in which the insulated pressure vessels will be installed and tested on two vehicles. A draft standard will also be generated for obtaining insulated pressure vessel certification.

INTRODUCTION

Hydrogen and natural gas-fueled vehicles have many features that make them serious candidates as alternatives to today's petroleum-powered vehicles. Hydrogen and natural gas vehicles can use advanced technologies to greatly improve environmental quality, reducing to practically zero automotive emissions of regulated pollutants. Greenhouse gas emissions can also be considerably reduced, with the potential of achieving a carbon-free system if hydrogen is obtained from renewable sources. At the same time, hydrogen and natural gas vehicles have the capability of providing the range, performance, and utility of today's gasoline vehicles. Natural gas is a short-term solution that has considerable advantages compared to petroleum-based fuels. Hydrogen vehicles are the best long-term solution to our energy and environmental problems associated with transportation.

The work described here will contribute in great part to solving the most important problem associated with hydrogen and natural gas-fueled vehicles. This is the problem of storage, which is especially critical for hydrogen. While other problems are often cited as obstacles for the introduction of hydrogen-fueled vehicles (i.e. lack of infrastructure or high cost of fuel cells), storage is the biggest hurdle for introducing light-duty hydrogen-fueled vehicles into the market.

There are at least three technologies for storing hydrogen fuel in cars. These are compressed hydrogen gas (CH_2), metal hydride adsorption, and cryogenic liquid hydrogen (LH_2). Each of these has significant disadvantages. Storage of CH_2 requires a volume so big that it is difficult to package in light-duty cars. The big pressure vessel required for compressed hydrogen storage is also likely to be expensive. Hydrides are extremely heavy, resulting in a substantial reduction in vehicle fuel economy and performance. Low-pressure LH_2 storage is light and compact, and has received significant attention due to its advantages for packaging. Disadvantages of low-pressure LH_2 storage are the substantial amount of electricity required for liquefying the hydrogen; the evaporation losses that may occur during fueling low-pressure LH_2 tanks; and the evaporation losses that occur during periods of inactivity, due to heat transfer from the environment. In extreme cases, all of the fuel may evaporate, leaving the driver stranded and causing a serious inconvenience and a safety hazard. In addition to this, liquefaction of hydrogen introduces a significant energy penalty. Electricity consumption for liquefaction is about 40% of the lower heating value of the hydrogen.

Vehicular storage of natural gas is also a problem. Even at elevated pressure, compressed natural gas (CNG) has a very low density compared to gasoline or diesel fuels. Pressure vessels for natural gas are big and expensive, taking up most of the trunk space in a light-duty vehicle. Another option for storing natural gas is as a cryogenic liquid at low pressure (liquefied natural gas, LNG). LNG storage is light and compact, and is selected mainly in application to trucks, which are driven daily for long distances. Light-duty vehicles generally have a short daily range. For light-duty vehicles, use of LNG also has the disadvantage of resulting in substantial evaporative losses.

The alternative to vehicular hydrogen and natural gas storage proposed here consists of storing the fuel in an insulated pressure vessel that has the capability to operate at cryogenic temperature (as low as 20 K for LH_2), and at high pressure (24.8 MPa; 3600 psi). This vessel has the flexibility of accepting cryogenic liquid as well as compressed gas as a fuel. Filling the vessel with ambient-temperature compressed gas reduces the amount of fuel stored (and therefore the vehicle range) to about a third of its value with cryogenic liquid.

The fueling flexibility of the insulated pressure vessels results in significant advantages. Insulated pressure vessels have similar packaging characteristics as cryogenic liquid fuel tanks (low weight and volume), with reduced energy consumption for liquefaction. Energy requirements for fuel liquefaction are lower than for conventional, low-pressure cryogenic fuel tanks because a car with an insulated pressure vessel can use, but does not require, cryogenic fuel. A hybrid or fuel cell vehicle with 34 km/l (80 mpg) gasoline-equivalent fuel economy could be refueled with ambient-temperature compressed hydrogen at 24.8 MPa (3600 psi) and still achieve a 200 km range, suitable for the majority of trips. The additional energy, cost, and technological effort for cryogenic refueling need only be undertaken (and paid for) when the additional range is required for longer trips. With an insulated pressure vessel, vehicles can refuel most of the time with ambient-temperature compressed fuel, using less energy, and most likely at lower ultimate cost than cryogenic liquid fuel, but with the capability of having almost 3 times the range of room-temperature storage systems. Use of compressed hydrogen in all trips under 240 km (which represent 85% of all the distance traveled in the USA) reduces the total energy consumption by 16% over the energy consumed by a vehicle that is always filled with LH_2.

In addition to this, insulated pressure vessels also have much reduced evaporative losses compared to low-pressure cryogenic liquid fuel tanks. This has been demonstrated through an analysis of evaporative losses in cryogenic pressure vessels based on the first law of thermodynamics. Figures 1 and 2 illustrate the main results for hydrogen. Similar results are obtained for natural gas. Figure 1 shows hydrogen losses during vehicle operation. The figure assumes that two vehicles are fitted with cryogenic hydrogen storage tanks with the same capacity (5 kg). One vehicle has a low-pressure (0.5 MPa; 70 psi maximum) conventional liquid hydrogen tank, and the other has an insulated pressure vessel. The vehicles are identical in every respect, except for the tanks. The vessels are filled to full capacity with liquid hydrogen, and then the vehicles are driven a fixed distance every day. When the fuel runs out, the amount of fuel burned by the engine and the amount of fuel lost to evaporation are calculated, and the results are shown in Figure 1. The figure shows total cumulative evaporative hydrogen losses out of a full tank as a function of the daily driving distance, for a high-efficiency vehicle (34 km/l or 80 mpg gasoline equivalent fuel economy). As expected, evaporative losses increase as the daily driving distance is reduced, because less driving results in a longer time for hydrogen evaporation. The figure shows that a low-pressure LH_2 tank loses hydrogen even when driven 100 km per day. Losses from a LH_2 tank grow rapidly as the daily driving distance drops. A vehicle driven 50 km per day (the average for the USA) loses almost 1 kg (20%) of the fuel to evaporation. On the other hand, insulated pressure vessels lose hydrogen only for very short daily driving distances (less than 5 km/day). Most vehicles are driven considerably more than this distance, so that most vehicles equipped with an insulated pressure vessel would never lose any hydrogen to evaporation.

Figure 2 shows losses for a parked vehicle. The figure shows cumulative hydrogen losses as a function of the number of days that the vehicle remains idle. The most unfavorable condition is assumed: the vehicles are parked immediately after fueling. The low-pressure LH_2 tank has 2 days of dormancy (2 days without fuel loss) before any hydrogen has to be vented. After this, losses increase quickly, and practically all of the hydrogen is lost after 15 days. This may represent a significant inconvenience to a driver, who may be unable to operate the vehicle after a long period of parking. Insulated pressure vessels have a much longer dormancy (up to 16 days). Total losses for the insulated pressure vessel with MLVSI is only 1 kg after 1 month of parking. In addition to this, insulated pressure vessels retain about a third of their total capacity even when they reach thermal equilibrium with the environment after a very long idle time because of their high-pressure capacity. Therefore, the vehicle never runs out of fuel during a long idle period.

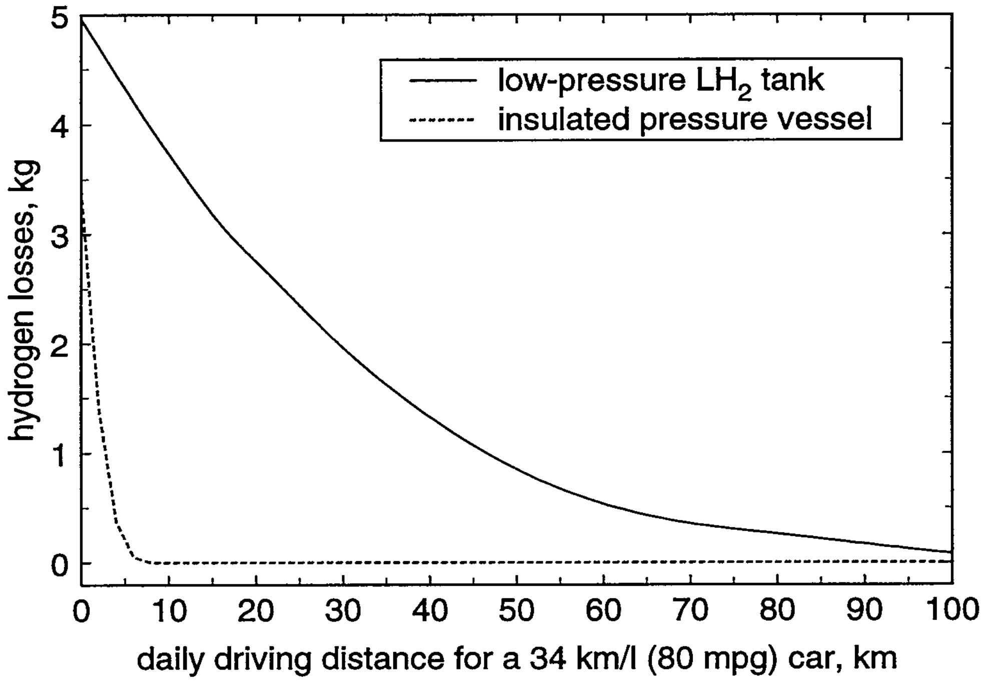

Figure 1. Cumulative hydrogen losses in kg as a function of daily driving distance, for vehicles with 34 km/liter (80 mpg) gasoline-equivalent fuel economy, for the LH_2 tank and the insulated pressure vessel, assuming that the vessels are initially full.

Insulated pressure vessels have the additional advantage over low-pressure cryogenic fuel tanks of being able to deliver high-pressure fuel, which can be used in direct injected engines without the need of a high-pressure pump, which would add significant cost to the fuel delivery system.

From an engineering and economic perspective, insulated pressure vessels strike a versatile balance between the cost and bulk of ambient-temperature compressed fuel storage, and the energy efficiency, thermal insulation and evaporative losses of cryogenic storage. In summary, insulated pressure vessels offer flexibility and savings, both in terms of energy and cost. Compared to liquid hydrogen tanks, insulated pressure vessels save over 40% of the energy consumption, due to the reduced evaporative losses and the reduced need to liquefy hydrogen. Compared to compressed hydrogen storage, insulated pressure vessels offer a 50% cost reduction for the manufacture of the pressure vessel, due to the smaller vessel size required.

Considering all the potential benefits of insulated pressure vessels, it is important to determine what type of pressure vessel could be operated at both high pressure and cryogenic temperature. Of the available pressure vessel technologies commonly used for vehicular storage of natural gas [1] it appears that aluminum-lined, composite-wrapped vessels have the most desirable combination of properties for this application (low weight and affordable price). However, commercially available aluminum-composite pressure vessels are not designed for low temperature applications.

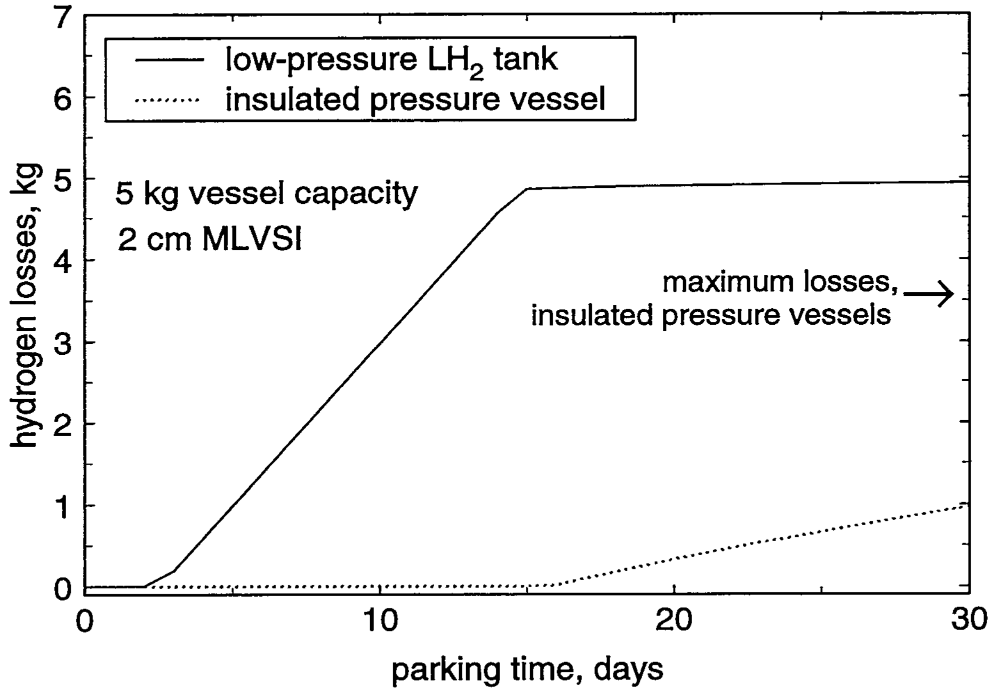

Figure 2. Cumulative hydrogen losses in kg as a function of the number of days that the vehicle remains idle, for the LH_2 tank and the insulated pressure vessel, assuming that the vessels are initially full.

This paper describes work in progress directed at evaluating the possibility of using commercially available aluminum-fiber pressure vessels at cryogenic temperatures and high pressures, as would be required for vehicular hydrogen or natural gas storage in insulated pressure vessels. The paper gives a description of previous and future tests. The purpose of these tests is to demonstrate that no technical barriers exist that prevent the use of aluminum-fiber pressure vessels at cryogenic temperatures. As a future task, we are planning to generate a draft for a certification standard which will be submitted to the relevant administrative bodies (DOT, ISO) for their consideration and approval. Another planned activity is a demonstration project in which insulated pressure vessels will be installed and tested on a vehicle.

PRESSURE VESSEL ANALYSIS AND TESTING

PRESSURE AND TEMPERATURE CYCLING: Pressure vessels have been cycled through 900 high-pressure cycles and 100 low-temperature cycles. The cycles are alternated, running 9 pressure cycles followed by a temperature cycle, and repeating this sequence 100 times. This test is expected to replicate what would happen if these vessels were used in a hydrogen or natural gas-fueled car. Liquid nitrogen is used for low-temperature cycling and gaseous helium for high-pressure cycling. To accomplish the required testing, an experimental setup has been built inside a high-pressure cell. An aramid-aluminum and a carbon fiber-aluminum pressure vessel have been cycled. The vessels have not failed during the test.

BURST TEST: The aramid-aluminum and the carbon fiber-aluminum pressure vessels were burst-tested after being cycled. The burst test was conducted according to the DOT standards [2]. Failure occurred by hoop mid cylinder separation, which is the preferred mode of failure. The burst pressure was 94.2 MPa (13.7 ksi), which is substantially higher than the minimum burst pressure of 72.4 MPa (10.5 ksi).

FINITE ELEMENT ANALYSIS: Cyclic and burst testing of the pressure vessels has been complemented with a finite element analysis. The finite element analysis is done to determine whether low temperature operation can result in damage to the pressure vessel. Finite element analysis has been conducted with a commercial finite element package [3]. A mesh has been developed. This is an axisymmetric mesh with 1195 elements. Sensitivity of the results to mesh resolution was tested by building a second mesh with 4234 elements. Little difference was observed between the Von Mises stresses obtained with the two grids. Physical properties of fiber-epoxy laminae were obtained from available literature at ambient and cryogenic temperatures [4,5]. Lamina properties are then converted into properties of the composite matrix. This is done by using a computer program [6]. This program assumes that the matrix is a homogeneous, orthotropic material. The properties of the matrix are then used in the finite element thermal and stress analysis.

Finite element analysis of the pressure vessel considers the manufacture of the pressure vessel, starting from the curing process and continuing with the autofrettage cycle. The autofrettage is a process in which the vessel is subjected to a high internal pressure (45.5 Mpa, 6600 psi, in this case) to introduce a level of plastic deformation and pre-stress. After the autofrettage, the vessel is subjected to a series of low temperature and high-pressure cycles. These are identical to the sequence used for the cyclic test of the pressure vessel, consisting of a cryogenic cycle down to liquid nitrogen temperature followed by nine pressure cycles up to the design pressure.

The results of the finite element analysis show that the autofrettage cycle introduces a high level of plastic deformation. After this, the cryogenic cycles also introduce some plastic deformation in the liner. However, successive cryogenic cycles introduce less and less plastic deformation, until the plastic deformation asymptotes to a value slightly higher than 4%. Further cycles do not increase the level of plastic deformation, and therefore the pressure vessel is not expected to fail due to repeated cryogenic cycles. This is in agreement with the cryogenic cyclic tests, in which the vessels were subjected to 100 cryogenic cycles with no damage or failure.

INSULATION DESIGN AND INSULATED PRESSURE VESSEL CONSTRUCTION: Insulated pressure vessels have been designed to operate with multilayer vacuum superinsulation (MLVSI). MLVSI has a good thermal performance only under a high vacuum, at a pressure lower than 0.01 Pa ($7.5x10^{-5}$ mm Hg [7]). Therefore, the use of MLVSI requires that an outer jacket be built around the vessel. Two designs for the insulation have been built: a first-generation design and a second-generation design. The first-generation vessel is a 1/5-scale vessel that stores about 1 kg of liquid hydrogen, and it is shown in Figure 3. This design has been built for cyclic testing and for DOT certification tests. The insulation design includes access for instrumentation for pressure, temperature and level, as well as safety devices to avoid failure in case the hydrogen leaks into the vacuum space. Five pressure vessels have been built according to the first-generation pressure vessel design. These vessels have been tested for compliance with DOT/ISO certification standards.

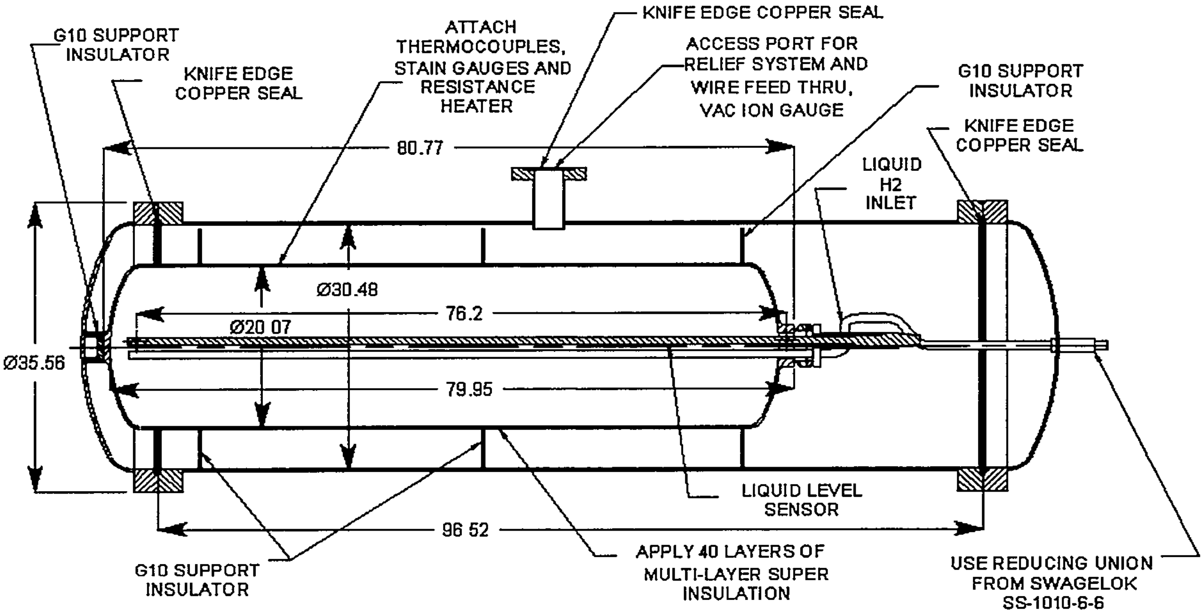

Figure 3. Insulation design for first-generation pressure vessel. The figure shows a vacuum space, for obtaining high thermal performance from the multilayer insulation, and instrumentation for pressure, temperature and level. Dimensions are given in cm.

The second-generation pressure vessel design is shown in Figure 4. This vessel can store about 8 kg of liquid hydrogen. This design includes a vapor shield to reduce evaporative losses in addition to the instrumentation and safety devices that exist in the first generation vessel. These vessels are currently being built. The second generation of pressure vessels will be used for DOT and SAE tests, and for incorporation into demonstration vehicles.

LIQUID AND GASEOUS HYDROGEN TESTING: A first-generation insulated pressure vessel has been tested with liquid and gaseous hydrogen. The vessel was first shock-tested and leak-tested. The insulated pressure vessel was then transported to a remote facility for testing with liquid hydrogen. Testing involved filling the vessel with

LH_2 to study the insulation performance, the performance of the sensors, and the problems involved with pumping the LH_2 into the vessel. This test is expected to replicate what would happen to the vessel during fueling and operation in an LH_2-fueled car. The test was conducted successfully. There was no damage to the vessel due to the low temperature operation, all the instrumentation operated properly at the low temperature.

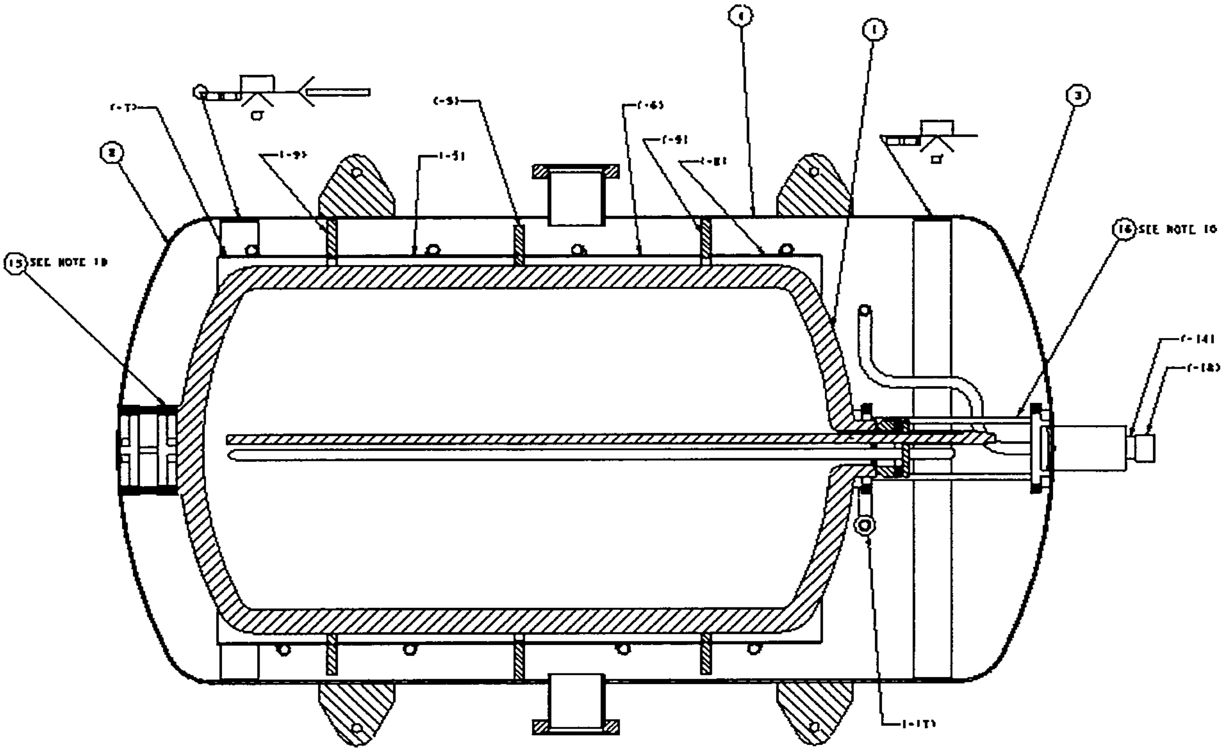

Figure 4. Insulation design for second-generation pressure vessel. The figure shows a vacuum space, for obtaining good performance from the multilayer insulation, instrumentation for pressure, temperature and level, and a vapor shield for reducing hydrogen evaporative losses.

DOT, ISO AND SAE CERTIFICATION TESTS: Along with the cryogenic cyclic tests and the finite element analysis, insulated pressure vessels are being subjected to certification tests according to the standards set by the Department of Transportation (DOT), the International Standards Organization (ISO) and the Society of Automotive Engineers (SAE). A list of the tests that may be relevant to insulated pressure vessels has been generated. The selected tests are listed next. So far the first six tests have been successfully completed. The only remaining tests are the cryogenic drop and fire tests.

- Cycling, Ambient Temperature [2].
- Cycling, Environmental [2].
- Cycling, Thermal [2].
- Gunfire [2].

- Bonfire [2].
- Drop Test from 3 m (10 ft) [2].
- Cryogenic drop tests from 10 m and 3 m [8].
- Flame test with cryogenic fill [8].

TECHNOLOGY VALIDATION AND CERTIFICATION

All tests and analysis conducted to date indicate that insulated pressure vessels can safely be used to store cryogenic and ambient temperature compressed hydrogen or natural gas for vehicular applications. The safety of insulated pressure vessels, along with their multiple advantages for vehicular fuel storage opens the way for future commercialization of this technology. However, two remaining tasks have the potential of considerably advance the technology on its way to commercialization. These are field demonstration and vessel certification. To accomplish these tasks we have teamed up with a major pressure vessel manufacturer (Structural Composites Industries, SCI, Pomona, CA, USA), and a transit authority with a broad interest on alternative fuel vehicles and environmental projects (SunLine, Thousand Palms, CA, USA). SCI provides a direct path for future commercialization of this technology, while SunLine is the ideal place to conduct a demonstration of the technology.

For a demonstration of the technology we are planning to install an insulated pressure vessel in a Ford Ranger pickup truck driven by a hydrogen engine. Another insulated pressure vessel will be installed in a LNG-fueled Ford F250 pickup truck. Installation will include instrumentation of the tank with sensors for level, temperature and pressure. The vehicle will then be tested for a period of six months. The trucks will be used as regular vehicles of the SunLine fleet. The drivers and service personnel will thoroughly document fuel use, instrumentation performance, vehicle performance, refuelability issues, etc. We will ask for their comments and work on addressing these comments. Finally, we will write a comprehensive report on the experiences obtained during testing of the vehicles. The report will contain all of the users' comments and observations generated during testing. These comments will then be used to develop improved pressure vessel designs and continue down the path toward commercialization.

For the development of a procedure for vessel certification, we will start by studying existing pressure vessel standards (Department of Transportation, DOT; Society of Automotive Engineers, SAE; National Fire Protection Association, NFPA; American Society of Mechanical Engineers, ASME; etc.), to determine which of those can be applied to insulated pressure vessels. The existing standards will be carefully studied for their potential incorporation into a list of standards for insulated pressure vessels. Additional tests may be included in the list if considered necessary to address the safety of cryogenic operation of pressure vessels. Finally, we will write a report detailing the proposed standards. The proposed standards will be circulated to industry for comments. After incorporating the comments, the final standards will be submitted to the regulating agencies (SAE, DOT, and ISO) for their consideration.

CONCLUSIONS

Insulated pressure vessels are being developed as an alternative technology for storage of hydrogen and natural gas in light-duty vehicles. Insulated pressure vessels can be fueled with either liquid or compressed fuel. This flexibility results in advantages compared to conventional storage technologies. Insulated pressure vessels are lighter than hydrides, more compact than ambient-temperature pressure vessels, and require less energy for liquefaction and have less evaporative losses than liquid fuel tanks.

For reduced cost and complexity it is desirable to use commercially available aluminum-fiber pressure vessels for insulated pressure vessels. However, commercially available pressure vessels are not designed for operation at cryogenic temperature. A series of tests has been carried out to verify that commercially available pressure vessels can be operated at cryogenic temperature with no performance losses. All analysis and experiments to date indicate that no significant damage has resulted. Future activities include a demonstration project in which the insulated pressure vessels will be installed and tested on two vehicles. A draft standard will also be generated for obtaining certification for insulated pressure vessels.

ACKNOWLEDGMENTS

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